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Assessment of Groundwater Potential and Mapping of Aquifer Protective Capacity in Parts of Bauchi Metropolis, Northeast Nigeria, Using Dar-Zarrouk Parameters derived from Geoelectrical Resistivity Data

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Abstract

Sustainable groundwater governance in urban crystalline basement terrains requires reliable assessment of groundwater potential and aquifer vulnerability to surface-derived contamination. This study evaluates groundwater potential and aquifer protective capacity within Unity Estate, along Jos Road, Bauchi Metropolis, Nigeria, using Dar-Zarrouk parameters derived from geoelectrical resistivity data and supported by hydrochemical information. Ten Vertical Electrical Sounding (VES) stations were established using the Schlumberger electrode configuration, with current electrode half-spacing (AB/2) extended to 60 m. Quantitative interpretation of the VES data identified conventional A-, H-, and HA-type curve signatures, reflecting variations in subsurface lithology and geoelectrical conditions. Layer resistivities and thicknesses obtained from the interpreted models were used to calculate the Dar-Zarrouk parameters comprising longitudinal conductance (S), transverse resistance (T), and coefficient of anisotropy (λ). Longitudinal conductance values ranged from 0.013 - 0.890 S, indicating predominantly weak aquifer protective capacity across the study area. Transverse resistance varied from 4,776 - 21,010 Ωm^2, demonstrating considerable subsurface heterogeneity, while anisotropy coefficients of 1.23 – 1.58 indicate moderate to significant geoelectrical variability. Vulnerability classifications were further corroborated using hydrochemical data from selected wells. Three groundwater potential zones were delineated. High-potential zones were associated particularly with VES stations displaying A-type curves characterised by low-resistivity layers at depth, interpreted as weathered or fractured basement aquifers. Aquifer protective-capacity mapping revealed that 60% of the investigated area possesses weak-to-moderate protective capacity and is consequently susceptible to surface-derived contamination. The integrated geoelectrical and hydrochemical approach provides a robust framework for groundwater exploration, aquifer vulnerability assessment, and sustainable groundwater-resource management in Bauchi Metropolis.

Keywords
Groundwater Potential,
Aquifer Protective Capacity,
Dar-Zarrouk Parameters,
Geoelectrical Resistivity,
Bauchi Metropolis

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1. Introduction

In areas with crystalline basements, groundwater is the most reliable source of drinking water. This is especially true in semi-arid countries that have surface water resources that are either restricted or unreliable. According to Ibrahim et al. (2024) and Egbueri et al. (2025), more than seventy-five percent of Nigerians rely on groundwater for their home and agricultural requirements. This is especially true in the northeastern region, which is an area that is particularly dependent on these water sources due to the absence of permanent surface water bodies. Due to the crystalline foundation complex that lies beneath huge parts of Nigeria, particularly in Bauchi State, groundwater research is met with a unique set of challenges.

According to Lawal et al.'s research from 2020, 2021, and 2023, the presence of groundwater is influenced by the secondary porosity that is produced as a result of the weathering and fracturing of igneous and metamorphic rocks. An amalgamation of geophysical and hydrogeological approaches is required for effective drilling site selection and groundwater resource evaluation (Rodriguez & Ferolin, 2024; Alao & Abubakar, 2025). This is due to the fact that the study of groundwater is impeded by the varied composition of aquifers, which needs the combination of these two procedures.

According to Adiat et al. (2024) and Adefehinti et al. (2025), geoelectrical resistivity techniques have become increasingly important instruments for groundwater research and aquifer characterisation in places with crystalline basements. Crystalline basements have been used as a setting for practicing these procedures. It has been stated by Sikandar et al. (2010) and Mensah et al. (2024) that the Vertical Electrical Sounding (VES) approach, namely the Schlumberger Array, is utilised extensively due to the fact that it is economical, it is simple to implement, and it has the capacity to generate accurate measurements of subsurface resistivity.

The examination of VES data can provide valuable insights into the underlying lithology of the sedimentary rocks. This information includes the identification of weathered layers, fractured zones, and entire bedrock (Holbrook et al., 2019; Avenbuan et al., 2025; Maurya et al., 2025). Parkhomenko (1982) and Telford et al. (1990) state that the key elements that determine the electrical resistivity of geological materials are the degree of saturation, porosity, moisture levels, clay mineral composition, and moisture content. Clay mineral composition is also a factor. In crystalline basement regions, lower resistivity measurements frequently suggest degraded or fractured zones that have the potential to function as aquifers, as stated by Ariyo and Adeyemi (2009) according to their findings. On the other hand, greater resistivity values correlate with pristine, solid bedrock that has a restricted groundwater potential.

Two of the factors that make up the Dar-Zarrouk parameters are the longitudinal conductance (S), the transverse resistance (T), and the anisotropy coefficient (λ). According to Akinlalu et al. (2018), these criteria offer a basis that may be measured for the purpose of analysing the features of aquifers and the capacity of those aquifers to protect or guide against pollution. The data on geoelectrical resistivity are the source of these characteristics, which have been utilised extensively in groundwater research across a wide variety of geological environments.

The capacity of the aquifer to guard against surface pollution is measured by the longitudinal conductance ($S = h/\rho$), which is defined as the proportion of layer thickness to resistivity (Egbueri et al., 2023 as stated in the aforementioned reference. Because the overburden layer presents a stronger barrier to the infiltration of pollutants, any increase in conductance measurements is indicative of an improvement in the protective efficacy of the material. Both the classification frameworks for protective capability based on longitudinal conductance and the classification frameworks themselves are well acknowledged:

> 10 Siemens: Excellent protective capacity
5 – 10 Siemens: Good protective capacity
0.7 – 5 Siemens: Moderate protective capacity
0.1 – 0.7 Siemens: Weak protective capacity
< 0.1 Siemens: Poor protective capacity (Egbueri et al., 2023)

According to Adeyemi et al. (2016), the Transverse Resistance (T) of an aquifer is a measure of its ability to carry electrical current in a direction that is perpendicular to the bedding planes. This level of resistance is calculated by multiplying the layer thickness by the resistivity ($T = h \times \rho$). Measurements of increased transverse resistance often indicate the presence of more resistive layers, which may indicate the presence of more resilient bedrock or sections that have been less eroded.

As described by Kumar et al. (2019), the coefficient of anisotropy (λ) is a measure of subsurface variability. It is calculated by taking the square root of the ratio of transverse resistance to longitudinal conductance ($\lambda = \sqrt{(T/S)}$). Values that are close to 1 suggest isotropic conditions, which represent a homogenous subsurface. On the other hand, values that are much beyond 1 indicate anisotropic conditions, which are characterised by a heterogeneous subsurface that is characterised by stratification or fracturing. Identifying fractured areas and aquifer potential regions in crystalline basement terrains has been accomplished by the utilisation of the anisotropy coefficient.

Geophysical studies have been conducted in Bauchi Metropolis aimed at groundwater exploration. The crystalline basement terrain of the metropolis has been subjected to hydrogeological investigations; nevertheless, comprehensive geoelectrical assessments alongside a detailed analysis of Dar-Zarrouk parameters have been lacking. Previous studies in this field have focused mostly on the hydrochemical assessment of groundwater quality, whereas the geophysical characterisation of aquifer systems has been largely overlooked (Tijjani et al., 2023).

This study addresses this shortcoming by conducting a systematic geoelectrical survey at Unity Estate, Jos Road, Bauchi, to assess groundwater potential and the aquifer's protective capability using the Dar-Zarrouk parameter approach with the aim of assessing the groundwater potential and aquifer protection capacity in some parts of the Metropolis by employing Dar-Zarrouk parameters derived from geoelectrical resistivity data; alongside the following specific objectives, which include:

i To determine the geoelectrical characteristics (layer resistivities and thicknesses) of the subsurface in Bauchi Metropolis by Vertical Electrical Sounding evaluations.

ii To compute the Dar-Zarrouk parameters, which encompass the longitudinal conductance (S), transverse resistance (T), and anisotropy coefficient (ʎ) for each and every VES station. This will allow for the generation of spatial distribution maps through the utilisation of Geographic Information System (GIS) techniques. These maps will illustrate the horizontal variability of groundwater potential and groundwater safeguarding capabilities.

iii To categorise the systems already in the study area into three groundwater potential zones: high, moderate, and low, and to additionally identify zones of aquifer protective capacity, for the purpose of facilitating sustainable water resource management and borehole site selection in the Bauchi Metropolis

The fact that this research takes a holistic approach is what makes it stand out from other studies. The purpose of this study is to give a comprehensive assessment of the groundwater resources in Bauchi Metropolis by incorporating geoelectrical resistivity analysis, Dar-Zarrouk parameter assessment, and GIS-based spatial mapping (Ojo et al., 2024; Nwokeabia et al., 2025). The findings will make it simpler to implement environmentally friendly groundwater management practices and will provide a scientific basis for the deployment of boreholes in the region that is the subject of the existing inquiry.

2. Study Area

Located in the Bauchi metropolitan area, within the Bauchi Local Government Area of Bauchi State, in the northeastern region of Nigeria, the research area known as Unity Estate along Jos Road is located at approximately latitudes 10°16'13.8" N and 10°16'19.4" N and longitudes 9°41'43.7" E and 9°41'50.2" E (Figure 1). Within the Sudan Savanna geographical zone, this region has a tropical continental climate that is characterised by times of intense rainfall and periods of drought (Adam et al., 2026; Saeed et al., 2026).

With the wet season running from May to October and the arid season spanning from November to April, the climate is controlled by the dynamics of the Inter-Tropical Discontinuity (ITD), which is a climatic variable (Odekunle et al., 2024; Ahmad, 2024). While the average daily temperature ranges from 20 degrees Celsius during the Harmattan period to over 38 degrees Celsius during the warmer months of March and April, the annual precipitation ranges from 800 to 1,100 millimetres (Andersen et al., 2005; Musa, 2021).

The research region is primarily distinguished by moderate undulations, and its elevations range from around 600 to 700 meters above the average sea level. Almustapha (2023) and Omar et al. (2025) have identified these geographical aspects as the defining characteristics of the region. Regular surface drainage takes place, with the majority of its manifestations taking place during the wet season. Surface drainage happens on a recurrent basis. In the end, it is discharged into the tributaries that are located within the Gongola River Basin (Abugu et al., 2024; Umar et al., 2026). One of the most prominent types of vegetation is the Sudan savanna, which is characterised by grasses, shrubs, and tree species that are able to survive in dry conditions. The indigenous vegetation, on the other hand, has undergone considerable transformations as a consequence of the expansion of urban territories (Abdullahi, 2020).

2.1 Geology and Hydrogeology

Within the Precambrian Basement Complex, which is located in the northeastern region of Nigeria, the Bauchi Metropolis is a part of both the Nigerian Basement Complex and the Trans-Saharan Mobile Belt. According to Dada et al. (2024), the region is mostly underlain by crystalline igneous and metamorphic rocks. These formations include migmatites, banded and granitic gneisses, older granites, granulites, and the famous fayalite-bearing quartz monzonite (Bauchite). During the Pan-African Orogeny, which occurred around 600 ± 150 million years ago, these rocks were formed and positioned. Since then, they have undergone extensive deformation, metamorphism, and extended tropical weathering. Faults, fractures, joints, and foliations that trend NE–SW and NW–SE are the topographical features that define the region. These features influence the geomorphology of the region and have an effect on the subsurface fluid dynamics. A regolith of varying thickness has been produced as a consequence of the erosion of these foundational rocks (Obaje, 2009; Ferré et al., 2026; Abdullahi et al., 2025). This regolith is composed of clayey weathered substances, clayey soils, partially weathered basement, and bedrock that has not been weathered.

According to Lawal et al. (2021), the fresh rocks in Bauchi Metropolis have little primary porosity, which means that groundwater predominantly exists in the weathered overburden and fractured crystalline basement. This classification categorises the hydrogeological system as a basement complex aquifer system. Resuscitation of groundwater occurs mostly through the uptake of precipitation by weathered and fractured strata, as opposed to borehole production, which is affected by the thickness of the regolith and the degree of rock fracturing (Nicolas, 2019; Fenta et al., 2022). Aquifer outputs are usually moderate, but they vary among regions according to structural and lithological factors. Despite its widespread use, groundwater quality is at risk from increasing urbanisation and human activities. This highlights the need for sustainable groundwater management and regular hydrogeochemical monitoring (Ferré et al., 2026; Ekeleme et al., 2024).

3. Materials and Methods.

3.2 Collection of Geophysical Data

3.2.1 Vertical Electrical Sounding (VES) Methodology

Ten sites within the study area were subjected to Vertical Electrical Sounding (VES) using the Schlumberger array design (Olayinka et al., 2010). The operational advantages of the Schlumberger configuration were the reason for its selection, according to Adeyemo et al. (2017) and Ojelabi et al. (2002). Among these benefits are improved efficiency in depth penetration, less exposure to near-surface lateral variations, and simplified field logistics.

3.2.2 Schlumberger Array Setup:

The Schlumberger configuration is distinguished by a symmetrical position of the current electrodes (A and B) relative to the midpoint and the potential electrodes (M and N) close to the middle (Ellis & Singer, 2007; Kirsch & Yaramanci, 2009). The measurable resistivity, represented by ρ_a, is determined using the following formula:

$$\rho_a = \pi \times \frac{(AB/2)^2 - (MN/2)^2}{2 \times (MN/2)} \times \frac{\Delta V}{I}$$

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equation where:

AB/2 = half the current electrode spacing (metres)

MN/2 = half the potential electrode spacing (metres)

ΔV = potential difference measured between M and N (millivolts)

I = current injected through A and B (milliamperes)

3.2.3 Field Protocol

The VES were carried out using AB/2 intervals beginning at 1.5 meters and going up to 60 meters. According to Pozdnyakova et al. (2001), the predicted electrode distance (MN/2) did not change for any of the measurements, which ensured that the geometric factor was consistent regardless of the measurements. At each electrode interval, clear resistivity data were collected, which resulted in the production of a resistivity-depth profile for each and every site.

The procedures used in the field were in accordance with the conventional geophysical standards:

- i Electrode Arrangement: The current and potential electrodes were orientated in a linear fashion, and the location of the VES station was determined to be in the middle of the arrangement.
- ii Using a resistivity meter, direct current was passed through the current electrodes in order to measure the resistance.
- iii An evaluation of the voltage was performed by measuring the difference in voltage that existed between the potential electrodes.
- iv The documentation of the data includes the observation of recorded apparent resistivity measurements for each electrode spacing.
- v According to Peixoto et al. (2025), the process of ensuring the quality of the data involved doing a number of evaluations at certain intervals in order to verify the data's consistency and integrity.

3.3 Data Analysis and Interpretation

3.3.1 Numerical Analysis

Quantitative analysis was performed on the VES data using a bifurcated methodology, which consisted of first partial curve matching followed by computational iteration (Bayowa et al., 2007).

Partial Curve Matching: A comparison was made between the resistivity curves that were observed in the field and the master curves that were theoretically derived for the Schlumberger setup. Through the process of correlating the field curves with the relevant auxiliary curves, the fundamental properties of the layer, such as its resistivity and thickness, were determined. Traditional two-layer, three-layer, and multi-layer frameworks were utilised in order to construct the master curves that were utilised (Carrara et al., 1994; Okolie et al., 2010).

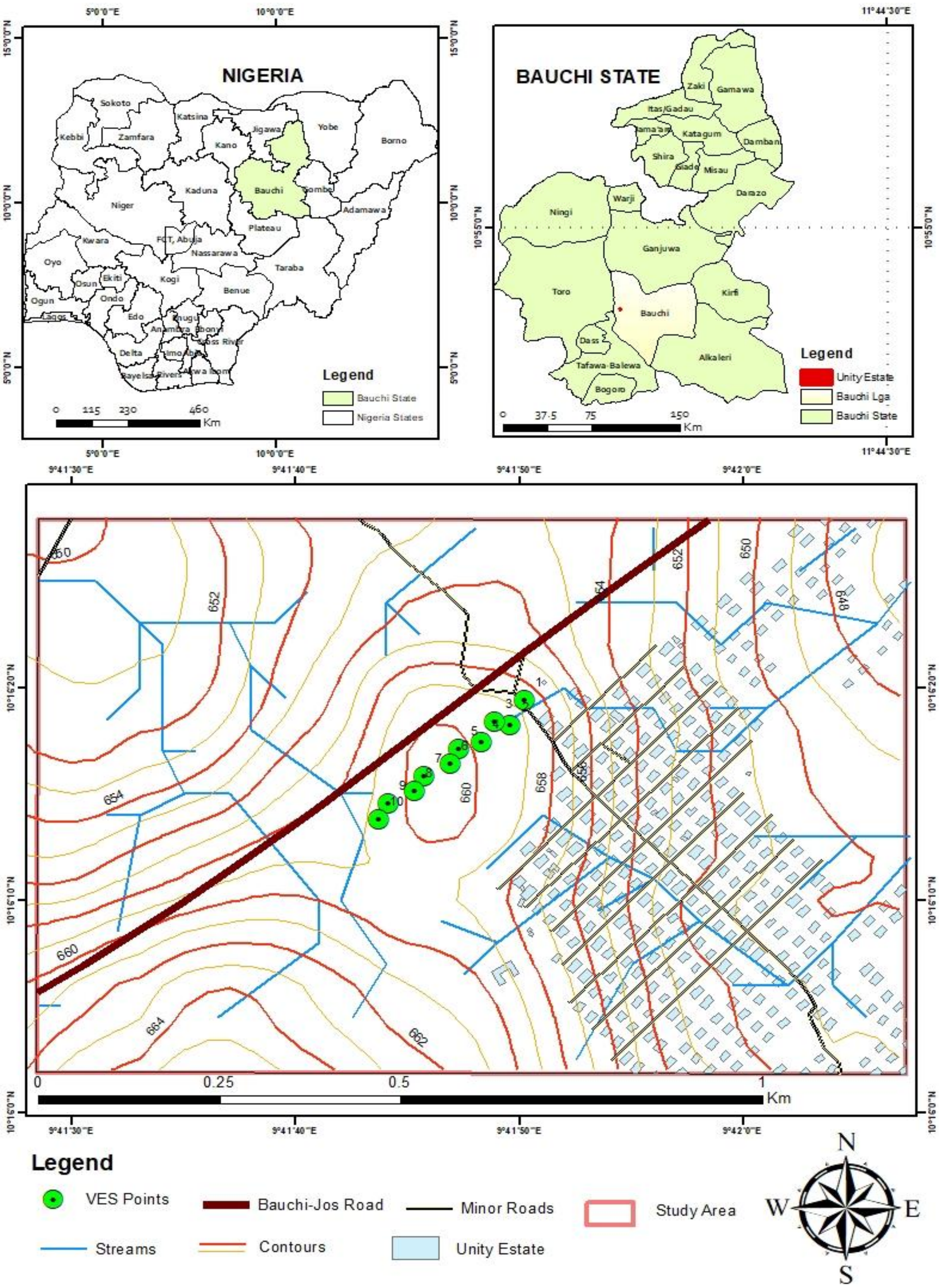

Figure 1. Map of the study area depicting topography and vertical electrical sounding points (NASA Shuttle Radar Topography Mission, 2013).

Computer Iteration: Through the use of repeated inversion techniques, the first layer parameters that were determined through partial curve matching were ultimately optimised. For the purpose of automatic inversion, the software applications IPI2WIN and RESIST were utilised. These applications were used to adjust the layer parameters in an iterative manner until the computed apparent resistivity curve coincided with the field data within acceptable error limits, which are typically 5% (Baba et al., 2026; Sajjad et al., 2026).

3.3.2 Extraction of Layer Parameters

The data from the VES that was evaluated provided layer specs for each station, which included the following:

i. Every subsurface stratum's electrical resistivity, measured in micrometres, is referred to as the layer resistivity (ρ_i). The measurement of the thickness of each underlying layer, expressed in meters, is referred to as the L Layer Thickness (h_i).

ii. "Count of Layers" refers to the number of geoelectrical layers that have been identified.

iii. Curve Classification refers to the classification of the VES curve, which includes examples such as A-type, H-type, and K-type.

3.4 Calculation of Dar-Zarrouk Parameters

3.4.1 Longitudinal Conductivity (S)

The longitudinal conductance (S) was determined for each VES station employing the formula:

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \cdots + \frac{h_n}{\rho_n}$$

where:

h_i = thickness of layer i (metres)

ρ_i = resistivity of layer i (Ωm)

n = number of layers

The protective capacity classification based on longitudinal conductance (Singh & Singh, 1970; Olorunfemi et al., 2020).

S Value (Siemens)	Protective Capacity Class
> 10	Excellent
5 - 10	Good
0.7 - 5	Moderate
0.1 - 0.7	Weak
< 0.1	Poor

3.4.2 Transverse Resistance (T)

Transverse resistance (T) was determined for each VES station employing the formula (Ameloko et al., 2022).

$$T = \sum_{i=1}^{n} h_i \times \rho_i = h_1\rho_1 + h_2\rho_2 + \cdots + h_n\rho_n$$

where:

h_i = measurement of layer i's thickness (in meters)

ρ_i = resistivity of layer i (Ohm-meter)

n represents the quantity of layers.

3.4.3 Anisotropy Coefficient (λ)

The anisotropy coefficient (λ) was determined for each VES station employing the formula:

$$\lambda = \sqrt{\frac{T}{S}} = \sqrt{\frac{\sum h_i \rho_i}{\sum h_i / \rho_i}}$$

where:

T denotes transverse resistance (Ωm^2).

S represents longitudinal conductance measured in Siemens.

3.5 Classification of Groundwater Potential

The potential of groundwater was classified in accordance with the features of the layers that were investigated and the classifications of the VES curve (Olorunfemi et al., 2019).

3.5.1 High Potential:

i. Low resistivity layers at depth, which are indicative of worn or cracked zones, are characterised by A-type curves.
ii. The presence of conductive layers, with a thickness of less than 100 Ωm, at depths more than 10 meters
iii. The transverse resistance values are exceptional, exceeding 2,000 Ωm^2, whereas the conductance is moderate.

3.5.2 Moderate Potential:

i. curves of the H-type or HA-type consisting of resistivity values that are intermediate
ii. Values of conductivity that are moderate (0.7 to 5 S)
iii. Weathered layers are present, but their thickness is rather low.

3.5.3 Low Potential:

i. The presence of high resistivity layers throughout (with a ρ greater than 500 Ωm) is indicative of the presence of fresh bedrock.
ii. Values of conductance that are less than 0.7 S
iii. Not having any significant areas that have been worn or broken

3.6 Spatial Analysis Using GIS

The software known as ArcGIS 10.8 was utilised in order to generate spatial distribution maps that depict Dar-Zarrouk features and groundwater potential classifications (Rahman, 2008). The following processes were employed in this process:

i. Coordinate Input: The coordinates of the VES station were entered into the environment of the GIS environment.
ii. Interpolation: The Kriging interpolation method was utilised in order to produce continuous surfaces for every Dar-Zarrouk parameter.
iii. categorisation: The interpolated surfaces were classed in accordance with the categorisation schemes that were previously created.
iv. The final maps illustrate the spatial distribution of groundwater potential and aquifer protective capacity. These maps were developed through the process of mapping.

4. Results and Discussions

4.1 Results

A qualitative evaluation of the different types of curves, a quantitative calculation of the layer characteristics (resitivities and thicknesses), a computation of the Dar-Zarrouk parameters, and a categorisation of the groundwater potential and aquifer protective capacity are covered by the interpretation. This section discusses the findings in relation to the geology and hydrogeology of the surrounding area, with a specific focus on the implications for groundwater exploration and management in the area under investigation.

4.1.1 *Geoelectrical Characteristics and Curve Types*

With one H-type curve (10%), one K-type curve (10%), and one HA-type curve (10%), the study of VES curves from all ten stations reveals that A-type curves predominate by a greater margin than any other form of curve. Table 1 provides a summary on the distribution of the curve type.

According to Zohdy et al. (1974), and Olayinka & Olorunfemi (1992), crystalline basement terrains are characterised by the prevalence of A-type curves. This is because resistivity increases with depth as a result of the transition from weathered, conductive overburden to fresh, resistant bedrock. The Nigerian Basement Complex is characterised by a typical weathering profile, which includes lateritic topsoil, weathered saprolite, fractured zone, and fresh bedrock. This pattern describes the normal weathering profile. On the other hand, the lack of H-type curves, which are the most indicative of favourable aquifer conditions, shows that the study area may have a restricted groundwater potential overall. This is in line with the usually thin weathering profiles that have been observed in the Bauchi area (Lawal, 2021).

VES 01 has a characteristic A-type curve, characterised by a gradual increase in apparent resistivity values, beginning at 433 Ω·m at AB/2 = 1.5 m and culminating in a peak of 2,748 Ω.Following a decrease to 843–1,779 Ω·m at maximum electrode spacing, the value of ·m at AB/2 = 20 m is recorded in Table 1 and Figure 1s. A particularly noteworthy phenomenon is the sudden rise in resistivity that occurs around AB/2 = 20 meters, which goes from 984 to 2,748 Ω·m. This increase indicates that the transition from weathered overburden to competent, resistive bedrock occurs at a relatively modest depth, perhaps 15–20 meters.

It is possible that lateral heterogeneity or the impact of a conductive layer at greater depth, possibly a saturated fracture zone, is the cause of the following decrease in apparent resistance that occurs at increasing electrode spacings. The existence of fresh basement at shallow depth and the relatively thin overburden are the two factors that contribute to the A-type curve at VES 01, which suggests that the groundwater potential is limited. According to Srivastava and Bhattacharya (2006) and Hasan et al. (2018), the absence of low-resistivity zones or zones with a resistivity of less than 100 Ω·m, which would indicate the presence of saturated weathered material, shows that this particular area is not suitable for groundwater development.

The VES 02 exhibits an A-type curve, characterised by starting resistivities of 12 Ω·m at AB/2 = 1.5–2.5 m. These resistivities subsequently grow to 219 Ω·m at AB/2 = 60 m, as shown in Table 1 and Figure 2s. The extremely low surface resistivities are indicative of the existence of conductive topsoil that is rich in clay or water-saturated material that is located near the substrate. There is a shift from clayey overburden to more resistant weathered basement, as indicated by the steady increase in resistivity with depth. However, the absence of high resistivity values (>500 Ω·m) at maximum electrode spacing suggests that fresh bedrock was not entirely penetrated within the current investigation depth.

Because of the low resistivities at shallow to intermediate depths (12–69 Ω·m), which may imply saturated conditions, VES 02 exhibits more favourable features for groundwater occurrence. This is despite the fact that it is classified as an A-type. A thick, clay-rich weathered profile that has the ability to provide some groundwater storage is indicated by the low resistivity values, as stated by Uhlemann et al. (2017) and Belle et al. (2019). These findings are based on the findings of the aforementioned researchers. On the other hand, these findings raise the possibility that the water quality has deteriorated as a consequence of the high clay level.

A curve of the A-type is displayed by VES 03, which demonstrates an initial resistivity of 216 Ω·m at a distance of 1.5 meters from the AB/2 point. Upon reaching a distance of 60 meters, the resistivity of this material rises to 1,896 Ω·m, as demonstrated in Table 1 and Figure 3s. On the other hand, the curve exhibits significant oscillations, with significant decreases occurring at AB/2 = 4 meters (300 Ω·m), 8 meters (446 Ω·m), and 20 meters (268 Ω·m). These drops in the curve are indicative of the presence of lithological heterogeneity. The general upward trend suggests that there is a transition from an overburden that is moderately resistive to a basement that is very resistive at great depth. This shift took place at a considerable depth. Given the oscillations that are present in the A-type curve at VES 03, it is clear that the subsurface is heterogeneous and has a restricted groundwater potential. According to Akanbi (2018) and Ameloko et al. (2022), the relatively high resistivities across the segment indicate that the weathered material is not completely saturated. Additionally, the presence of fresh basement at a modest depth restricts the storage capacity of the material throughout the section.

With apparent resistivity values decreasing from 25 Ω·m at AB/2 = 1.5 m to 16 Ω·m at AB/2 = 2.5 m, then increasing to 321 Ω·m at AB/2 = 15 m, and finally decreasing to 557 Ω·m at maximum electrode separation, VES 04 is the only station that displays a K-type curve, which is characterised by a low-high-low pattern (as shown in Table 1 and Figure 4s). Because the resistivity peak at intermediate depth (AB/2 = 15 m) may suggest the existence of a resistant layer (perhaps clay or severely worn material) overlaying a more conductive, water-saturated zone, the K-type pattern is particularly noteworthy hydrogeologically.

This is because the K-type pattern is characterised by a high degree of water saturation. In comparison to the other stations, the K-type curve at VES 04 is the one that is most advantageous for the occurrence of groundwater. A clay-rich topsoil is indicated by the low surface resistivities, whereas the intermediate resistive peak may be indicative of a zone with limited permeability depending on the circumstances. As one moves deeper into the ground, the resistivity decreases, which indicates the presence of a zone that is more conductive and likely saturated with water. This zone could be a cracked basement aquifer. The curve type at this station is the only one that indicates the presence of a confined or semi-confined aquifer at depth (Alkaabi et al., 2026; Dixit et al., 2026). Other stations have shown that this is the case.

VES 05 exhibits an A-type curve with initial resistivity of 73 Ω·m at AB/2 = 1.5 m, decreasing to 30 Ω·m at AB/2 = 4 m, then increasing progressively to 668 Ω·m at AB/2 = 60 m (Table 1, Figure 5s). The initial decrease followed by steady increase creates a partial H-type character, which may indicate the presence of a conductive layer (clay/saturated zone) near the surface followed by progressively more resistive material with depth. Despite the A-type classification, VES 05 shows moderate groundwater potential due to the low-resistivity zone at AB/2 = 4–8 m (30–49 Ω·m), which may indicate saturated conditions in the weathered material. However, the relatively high resistivities at depth suggest limited storage capacity and the presence of fresh basement at accessible depths (Aminu, 2015; Arowoogun & Osinowo, 2022).

VES 06 is the only station exhibiting a classic H-type curve ($\rho_1 > \rho_2 < \rho_3$), with resistivity values decreasing from 138 Ω·m at AB/2 = 1.5 m to a minimum of 43 Ω·m at AB/2 = 25 m, then increasing to 127 Ω·m at AB/2 = 60 m (Table 1, Figure 6s). The H-type pattern is diagnostic of a conductive layer—typically a saturated weathered or fractured zone—at intermediate depth between two more resistive layers (Orellana & Mooney, 1966). The minimum resistivity (43 Ω·m) corresponds to AB/2 ≈ 25 m, suggesting the presence of a water-saturated zone at approximately 15–25 m depth. The H-type curve at VES 06 is the most promising hydrogeological indicator in the study area. The low-resistivity zone (43–73 Ω·m) at intermediate depth (AB/2 = 20–40 m) is interpreted as a saturated weathered or fractured zone that could serve as an aquifer. The increase in resistivity at greater depth (115–127 Ω·m at AB/2 = 60 m) suggests the transition to more competent but still fractured basement, which may provide additional storage. This location is recommended as the highest priority for borehole development (Garba et al., 2026).

With a resistivity that continuously increases from 122–160 Ω·m at shallow depth to 1,006 Ω·m at AB/2 = 60 m, VES 07 displays a classic A-type curve, as shown in Table 1 and Figure 7s. The contour is smooth and progressive, which is indicative of a subsurface that is largely homogeneous and does not contain any significant lithological discontinuities or conductive layers. As a result of the thin overburden and the absence of low-resistivity (saturated) zones, the A-type curve at VES 07 suggests that the groundwater potential is limited. An indication of the existence of new bedrock can be inferred from the consistent rise in resistivities, which exceed 900 Ω·m. shallow depth, offering minimal groundwater storage (Hussain et al., 2022; Pavankumar et al., 2024).

VES 08 shows an A-type curve nearly identical to VES 07, with resistivity increasing from 112 Ω·m at AB/2 = 1.5 m to 1,006 Ω·m at AB/2 = 60 m (Table 1, Figure 8s). The similarity between VES 07 and VES 08 suggests lateral continuity of the subsurface lithology across this portion of the study area. Like VES 07, VES 08 shows limited groundwater potential due to the absence of saturated zones and the presence of fresh basement at shallow to moderate depth.

VES 09 exhibits the most pronounced A-type curve in the study area, with resistivity values increasing dramatically from 170–194 Ω·m at AB/2 = 1.5–6 m to 3,115 Ω·m at AB/2 = 60 m (Table 1, Fig. 9s). The curve shows an unusual resistivity spike at AB/2 = 8–10 m (1,868–2,068 Ω·m), followed by a decline to 700–811 Ω·m at AB/2 = 15–20 m, before increasing again to 2,799–3,115 Ω·m at maximum separation. Because of this pattern, it appears that there is a complicated lithological layering, possibly with interbedded resistive layers. A fresh bedrock that has not been weathered is present at a short depth, as shown by the extraordinarily high resistivities at VES 09, which are extremely high. According to Olatinsu and Salawudeen (2021) and Hasan et al. (2021), this particular location has the lowest groundwater potential in the entire research region. Additionally, there is no indication of saturated zones and the overburden thickness is modest.

VES 10 exhibits an **HA-type** curve (decrease-increase-decrease), with resistivity values initially increasing from 58 Ω·m at AB/2 = 1.5 m to 294 Ω·m at AB/2 = 20 m, then declining to 236–348 Ω·m at AB/2 = 60 m (Table 1, Fig. 10s). According to Orellana and Mooney (1966), the HA-type pattern is a variation of the H-type curve that may suggest the presence of a conductive layer at depth following an intermediate resistive peak during the process. It can be shown that the groundwater potential is moderate when the HA-type curve is at VES 10. A more conductive, perhaps water-saturated zone or fractured basement may be present at higher depths, as shown by the decreasing resistivity with depth, which supports the possibility of its presence. On the other hand, the relatively high resistivity readings (more than 200 Ω·m) in the lower zone that was interpreted indicate that the saturation may be restricted or that the fractures are not fully developed (Gemail et al., 2021).

Table 1: Distribution of VES Curve Types

Curve Type	VES Stations	Frequency (%)	Hydrogeological Significance
A-Type	01, 02, 03, 05, 07, 08, 09	70	Progressive coarsening/ competent basement; limited storage
H-Type	06	10	Saturated weathered/fractured zone; favourable aquifer
K-Type	04	10	Complex lithology; possible clay-capped aquifer
HA-Type	10	10	Complex weathering pattern; moderate potential
Total	10	100	-

4.1.2 Dar-Zarrouk Parameter Analysis

4.1.2.1 Computation of Dar-Zarrouk Parameters

Once the VES data were interpreted quantitatively, the Dar-Zarrouk parameters, which include longitudinal conductance (S), transverse resistance (T), and coefficient of anisotropy (ʎ), were calculated for every VES station. These parameters were determined by utilising the following relationships:

Longitudinal Conductance (S):

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} (\text{mhos})$$

Transverse Resistance (T):

$$T = \sum_{i=1}^{n} h_i \cdot \rho_i (\Omega \cdot \text{m}^2)$$

Coefficient of Anisotropy (ʎ):

$$\lambda = \frac{\sqrt{T/S}}{\sum_{i=1}^{n} h_i}$$

The computed parameters are presented in Table 2.

4.1.2.2 Interpretation of Longitudinal Conductance (S)

The values of longitudinal conductance (S) range from 0.013 mhos (VES 09) to 0.890 mhos (VES 04), with 0.189 mhos serving as the mean for the whole range. Tabular representation of the distribution of S values may be found in Table 2 and Figure 4.

A crucial finding that has substantial implications for the management of groundwater quality is the dominant presence of stations with inadequate protective capacity, which accounts for fifty percent of all stations. The longitudinal conductance is inversely connected to the vulnerability of the aquifer, as stated by Henriet (1976) and Oladapo and Akintorinwa (2007). Low S values suggest a thin, porous overburden that provides low protection against contaminants that are derived from the surface. It is possible that the entire research region is susceptible to pollution from surface sources, such as septic systems, home waste, and agricultural operations, because there is not a single station that possesses a good protective capacity (S > 0.7 mhos) (Ale, 2025; Chinyem et al., 2026).

In agreement with Olajide et al. (2020) and Bulus et al. (2022), VES 02 (0.274 mhos), VES 06 (0.212 mhos) had somewhat higher S values, suggests a modest level of protection. This may indicate the existence of an overburden that is thicker and more clay-rich, which could help to reduce the impact of pollutants to some extent. But even these numbers are below the 0.7 mhos threshold that is deemed sufficient for protection; therefore, it is clear that wellhead protection measures are needed everywhere.

As a result of the extremely low S values for VES 09 (0.013 mhos) and VES 01 (0.034 mhos), it is possible to draw the conclusion that there is essentially no capability for protection. According to Ameloko et al. (2022) and Mgbolu et al. (2024), any boreholes that were built in these locations would need to be surrounded by a deep casing and maintained under stringent sanitary protection. This is due to the fact that the groundwater in these regions is extremely vulnerable to pollution from the surrounding surface.

4.1.2.3 Interpretation of Transverse Resistance (T)

There is a wide range of values for transverse resistance (T), ranging from 4,776 $\Omega \cdot m^2$ (VES 06) to 21,010 $\Omega \cdot m^2$ (VES 04), with the mean value being 11,188 Ω·m3. The transverse resistance, in contrast to the longitudinal conductance, does not immediately indicate the protective capacity of the aquifer; rather, it represents the overall electrical character of the geo-electric section.

Higher T values represent thin overburden or unsaturated/resistive basement, while lower T values often indicate thicker, more conductive (saturated) weathered zones (Henriet, 1976; Soupios et al., 2007). This is because lower T values indicate that the weathered zones are more saturated. In light of this interpretation, which can be found in table 2 and Figure 5:

It is clear that there is an inverse relationship between temperature and groundwater potential. VES 06 has the lowest temperature and the highest inferred groundwater potential, whereas VES 01, 03, 07, 08, and 09 have high T values and a low groundwater potential. Bayewu et al. (2012) and Adiat et al. (2012) both found that this pattern is consistent with findings from basement terrains that are comparable to this one.

Table 2: Computed Dar-Zarrouk Parameters

VES Station	Curve Type	Total Thickness (m)	S (mhos)	T (Ω·m²)	λ	Groundwater Potential Rating
VES 01	A	20.4	0.034	12,291	1.47	Low
VES 02	A	38.5	0.274	12,930	1.23	Moderate
VES 03	A	17.3	0.039	8,505	1.42	Low
VES 04	K	32.5	0.890	21,010	1.58	Moderate-High
VES 05	A	15.8	0.147	9,292	1.28	Moderate
VES 06	H	28.7	0.212	4,776	1.39	High
VES 07	A	15.2	0.059	12,978	1.45	Low
VES 08	A	13.8	0.070	12,088	1.44	Low
VES 09	A	9.3	0.013	10,109	1.36	Very Low
VES 10	HA	32.4	0.156	7,895	1.33	Moderate

Table 3: Classification of Aquifer Protective Capacity Based on Longitudinal Conductance

Protective Capacity Class	S Range (mhos)	VES Stations	Frequency (%)
Good	> 0.7	None	0
Moderate	0.2 – 0.7	VES 02 (0.274), VES 06 (0.212)	20
Weak	0.1 – 0.2	VES 05 (0.147), VES 10 (0.156)	20
Poor	< 0.1	VES 01 (0.034), VES 03 (0.039), VES 07 (0.059), VES 08 (0.070), VES 09 (0.013)	50
Total	-	10	100

Table 4: Classification of Aquifer Protective Capacity Based on Transverse Resistance (T)

VES Station(s)	Curve Type	Transverse Resistance (T, Ω·m²)	Relative Level	Interpretation	Groundwater Potential
VES 06	H	4,776 *(Lowest)*	Lowest	• Lowest transverse resistance, indicating the thickest, most conductive (potentially saturated) weathered zone.	Highest (Best Potential)
VES 04	K	21,010 *(Highest)*	Highest	• Highest transverse resistance, indicating the most resistive section, yet paradoxically this station shows moderate groundwater potential due to the K-type curve indicating a possible aquifer at depth.	Moderate (Paradoxical)
VES 02	A	12,930 *(Moderate)*	Moderate	• Moderate transverse resistance, consistent with the A-type curve and moderate groundwater potential.	Moderate (Moderate Potential)
VES 01, 03, 07, 08, 09	A	> 8,000 *(High)*	High	• High transverse resistance, indicating thin overburden and limited groundwater potential.	Low to Very Low (Limited Potential)

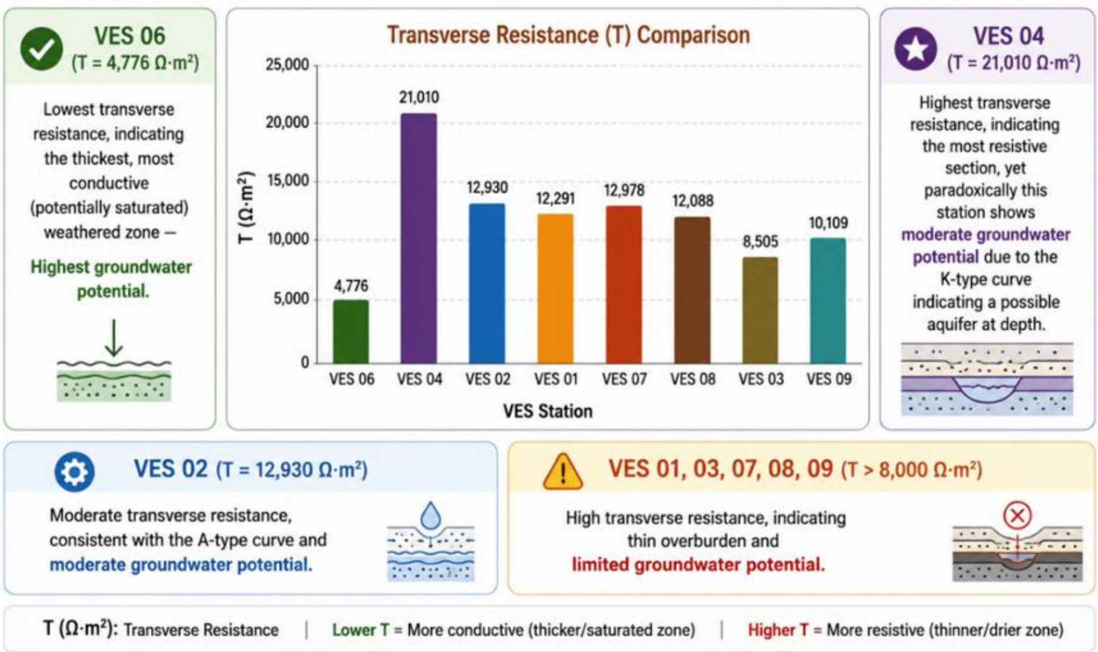

Figure 2. Classification of Aquifer Protective Capacity Based on Transverse Resistance (T)

4.1.2.4 Interpretation of Coefficient of Anisotropy (Λ)

The coefficient of anisotropy (Λ) values exhibits a wide range, ranging from 1.23 (VES 02) to 1.58 (VES 04), with a mean value of 1.40. (Table 2) According to Soupios et al. (2007), the coefficient of anisotropy is a measure of the degree of vertical heterogeneity in the subsurface. Values that are close to unity indicate that the conditions are isotropic, while values that are greater indicate that the anisotropy is increasing progressively as shown in Figure 6. According to Adabanija et al. (2021), the research area exhibits moderate to high anisotropy values, with a mean λ value of 1.40. This indicates that the subsurface is vertically heterogeneous, which is a feature of weathering profiles in crystalline basement terrains. The anisotropy that is strongest at VES 04 (λ = 1.58) may be an indication of considerable vertical fracturing or bedding, which has the potential to contribute to the enhancement of groundwater recharge and pollutant transfer.

4.1.2.5 Relationship Between Dar-Zarrouk Parameters and Groundwater Potential

The integration of S, T, and λ values provide a comprehensive assessment of groundwater potential and aquifer protective capacity (Shailaja et al., (2019).

4.1.3 Groundwater Potential Zonation

Based on the integrated analysis of curve types, Dar-Zarrouk parameters, and interpreted layer characteristics, the study area is classified into three groundwater potential zones:

4.1.3.1 High Groundwater Potential Zone (VES 06)

Characteristics:

i H-type curve
ii Low transverse resistance (T = 4,776 Ω·m²)
iii Moderate longitudinal conductance (S = 0.212 mhos)
iv Low-resistivity zone (43–73 Ω·m) at 15–25 m depth
v Total thickness > 28 m

VES 06 exhibits the most favourable hydrogeological characteristics, with a thick, saturated weathered/fractured zone indicated by the low-resistivity trough in the H-type curve. The moderate S value indicates some protective capacity, while the low T value confirms the presence of a conductive, potentially water-bearing layer. This location is recommended as the highest priority for borehole development (Okonkwo & Emmanuel, 2026).

4.1.3.2 Moderate Groundwater Potential Zone (VES 02, 04, 05, 10)

Characteristics:

i A-type (VES 02, 05), K-type (VES 04), HA-type (VES 10)
ii Moderate transverse resistance (T = 4,776–12,930 Ω·m²)
iii Weak to moderate longitudinal conductance (S = 0.147–0.274 mhos)
iv Low-to-moderate resistivity zones at intermediate depth
v Total thickness 16–38 m

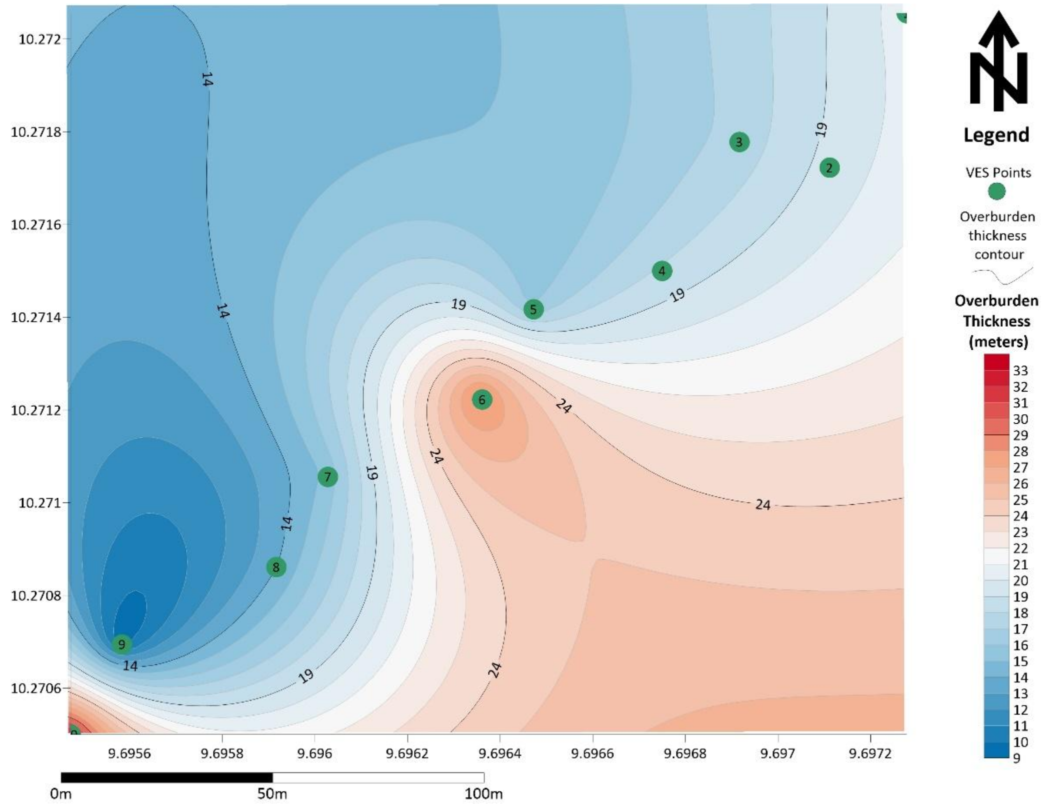

Figure 3. Overburden thickness of the aquifer protective capacity of the study area

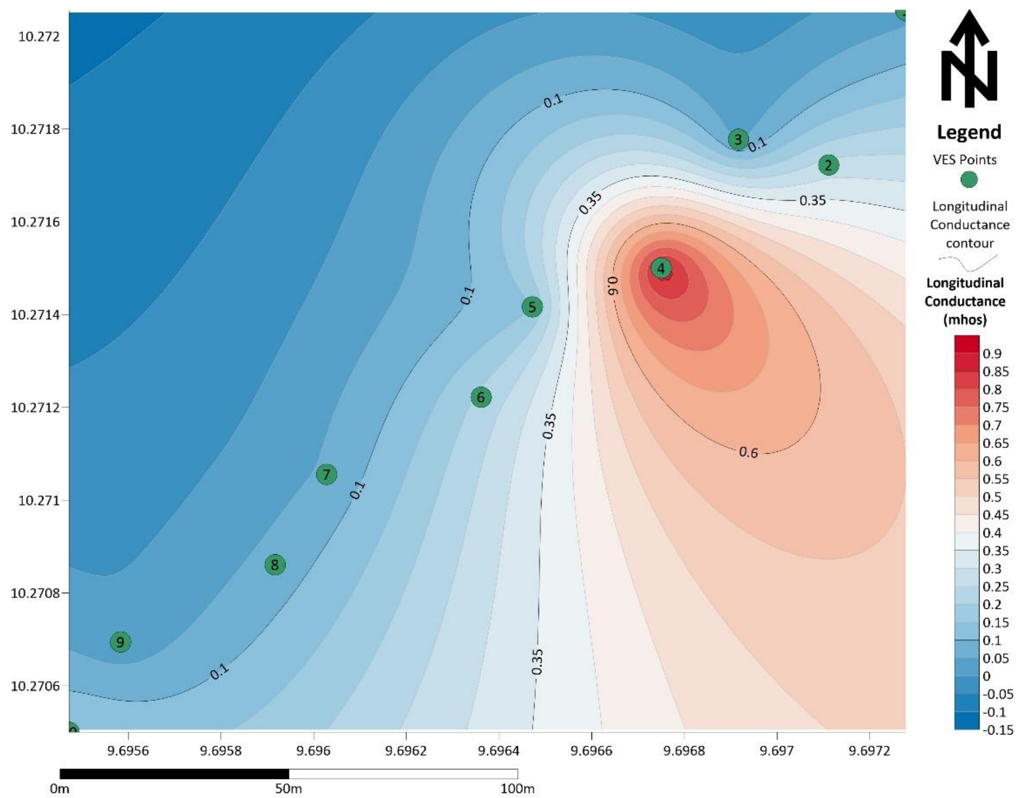

Figure 4. Longitudinal conductance of the aquifer protective capacity of the study area

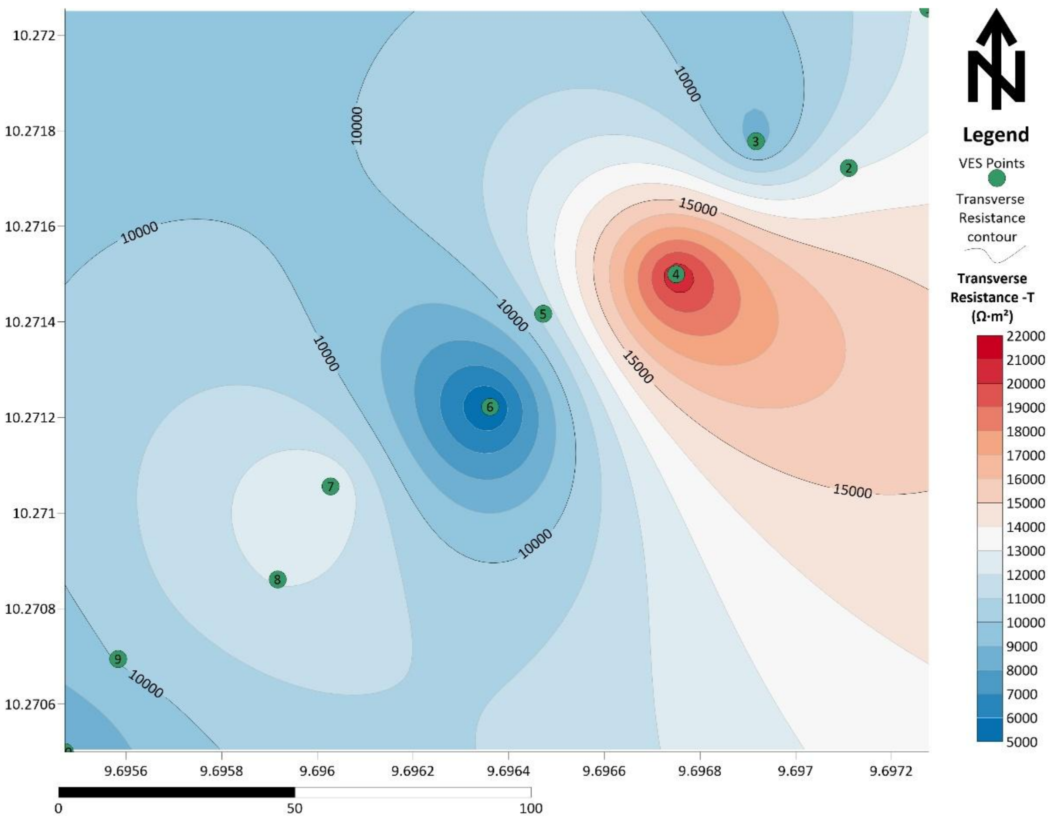

Figure 5. Transverse Resistance of the aquifer protective capacity of the study area

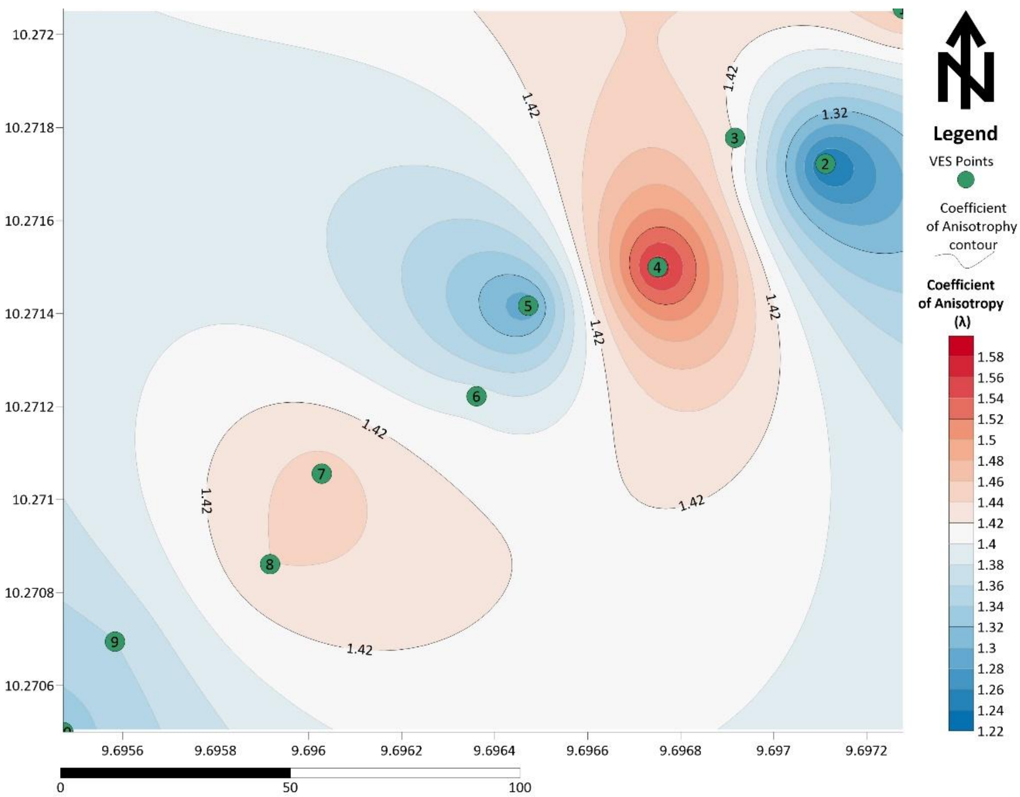

Figure 6. Coefficient of Anisotrophy of the aquifer protective capacity of the study area

Table 5. Classification of Aquifer Protective Capacity Coefficient of Anisotropy (λ)

VES Station(s)	λ (Coefficient of Anisotropy)	Anisotropy Level	Curve Type	Interpretation
VES 04	1.58	Highest	K	• Highest anisotropy, indicating significant vertical heterogeneity, likely due to alternating permeable and impermeable layers (clay-sand sequence) consistent with the K-type curve. This may enhance vertical hydraulic connectivity but also increase vulnerability to downward contaminant migration.
VES 01, VES 03, VES 07	1.47, 1.42, 1.45	High	A	• High anisotropy associated with A-type curves, indicating vertical heterogeneity due to weathering gradients.
VES 06	1.39	Moderate	H	• Moderate anisotropy, indicating a relatively homogeneous weathered profile, consistent with the H-type curve suggesting uniform saturated conditions.
VES 02	1.23	Lowest	A	• Lowest anisotropy, indicating the most homogeneous subsurface, with relatively uniform resistivity throughout the weathered column.

These stations show moderate groundwater potential with variable characteristics. VES 04 (K-type) is particularly notable as it may indicate a confined aquifer at depth, though the very low S value (0.039 mhos) indicates poor protective capacity. VES 02, 05, and 10 show moderate potential with weak to moderate protective capacity. These locations are recommended for borehole development with appropriate sanitary protection measures (Obiora et al., 2015; Oseji et al., 2018).

4.1.3.3 Low Groundwater Potential Zone (VES 01, 03, 07, 08, 09)

Characteristics:

i A-type curves
ii High transverse resistance (T = 8,505–12,978 Ω·m²)
iii Poor longitudinal conductance (S = 0.013–0.070 mhos)
iv High resistivities at depth (>500 Ω·m)
v Thin overburden (9–20 m)

These stations show limited groundwater potential due to thin overburden, absence of saturated zones, and the presence of fresh, resistive basement at shallow depth. VES 09, with the lowest S value (0.013 mhos) and thinnest overburden (9.3 m), is the least favourable location. Borehole development in these areas is not recommended without further detailed investigation (Fashae et al., 2014; Ameloko et al., 2022).

Table 6: Integrated Classification of Groundwater Potential and Protective Capacity

VES Station	Groundwater Potential	Protective Capacity	Recommended Action
VES 01	Low	Poor	Not recommended
VES 02	Moderate	Moderate	Recommended with sanitary protection
VES 03	Low	Poor	Not recommended
VES 04	Moderate-High	Poor*	Recommended with caution
VES 05	Moderate	Weak	Recommended with sanitary protection
VES 06	High	Moderate	Highest priority
VES 07	Low	Poor	Not recommended
VES 08	Low	Poor	Not recommended
VES 09	Very Low	Poor	Not recommended
VES 10	Moderate	Weak	Recommended with sanitary protection

*VES 04 shows poor protective capacity despite moderate-high potential, due to low S value.

4.1.4 Aquifer Protective Capacity Zonation

Based on the longitudinal conductance values (S), the study area is classified into four protective capacity zones:

4.1.4.1 Moderate Protective Capacity (VES 02, 06)

i S = 0.212–0.274 mhos
ii 20% of stations
iii Provides some attenuation of surface contaminants
iv Recommended for borehole development with standard sanitary measures

4.1.4.2 Weak Protective Capacity (VES 05, 10)

i S = 0.147–0.156 mhos
ii 20% of stations
iii Limited attenuation capacity
iv Boreholes require enhanced sanitary protection

4.1.4.3 Poor Protective Capacity (VES 01, 03, 04, 07, 08, 09)

i S = 0.013–0.070 mhos
ii 50% of stations
iii Virtually no attenuation capacity
iv Groundwater highly vulnerable to contamination
v Deep casing and stringent protection required if boreholes are developed

4.1.4.4 Good Protective Capacity

i None of the stations show good protective capacity (S > 0.7 mhos)
ii This is a significant finding indicating the study area's overall vulnerability to groundwater contamination

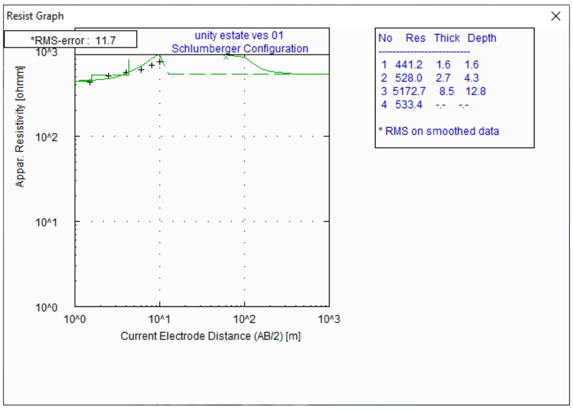

Fig. 1s: VES Resist Graph

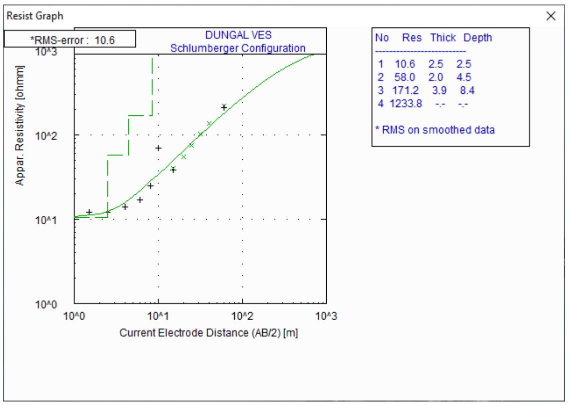

Fig.2s: VES Resist Graph

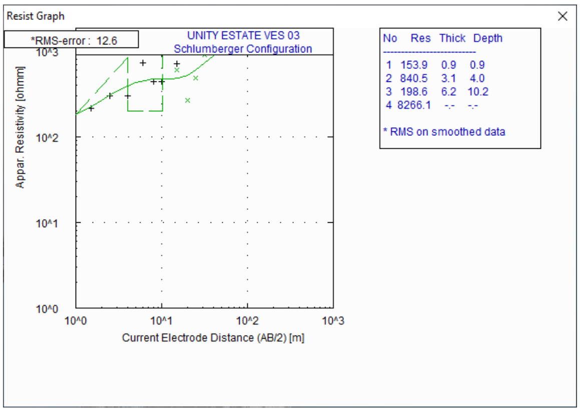

Fig. 3s: VES Resist Graph

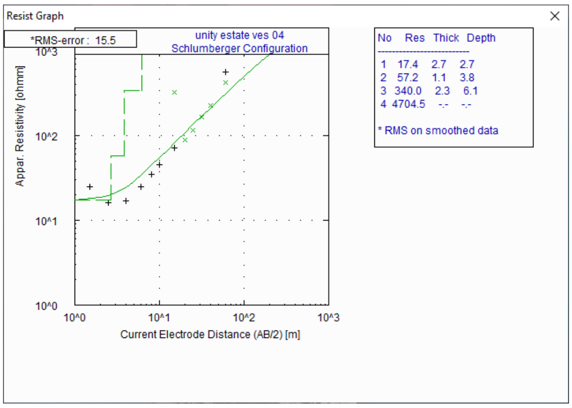

Fig. 4s: VES Resist Graph

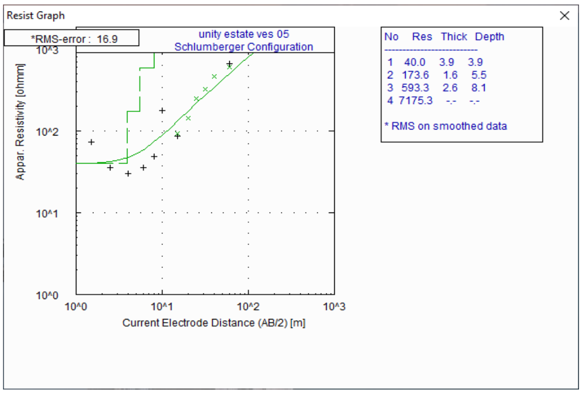

Fig. 5s: VES Resist Graph

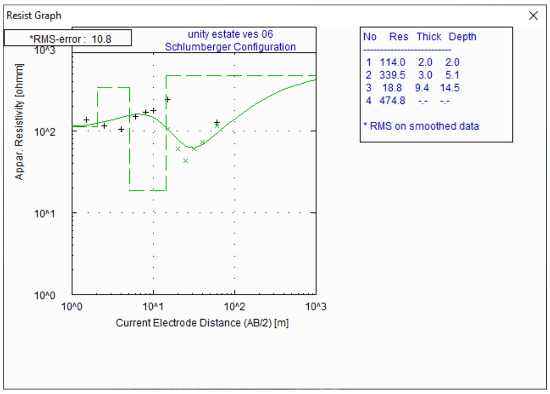

Fig. 6s: VES Resist Graph

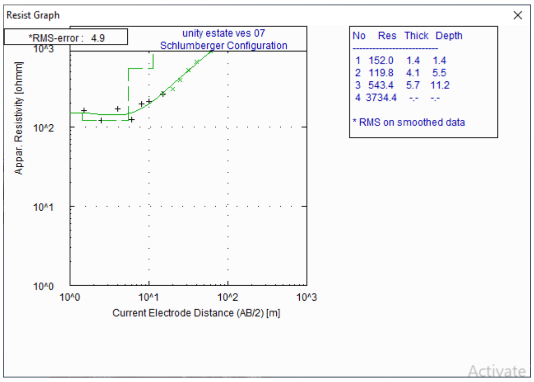

Fig. 7s: VES Resist Graph

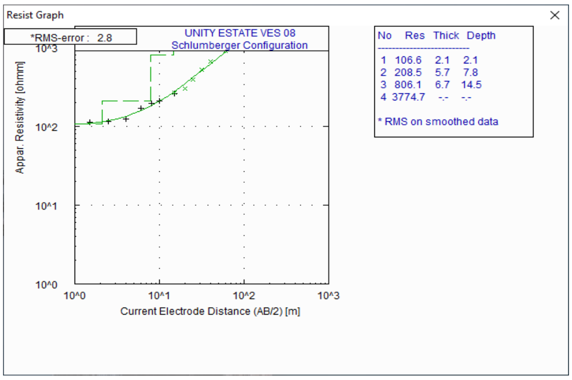

Fig. 8s: VES Resist Graph

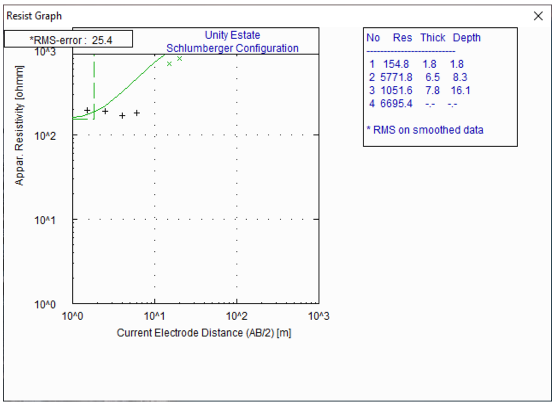

Fig. 9s: VES Resist Graph

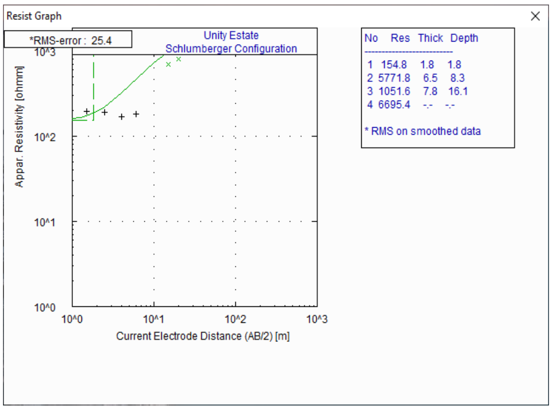

Fig. 10s: VES Resist Graph

4.2 Discussion of Results

4.2.1 Comparison with Regional Studies

The findings of this study are consistent with hydrogeophysical investigations in other crystalline basement terrains of northern Nigeria. Alaya et al. (2026) documented similar A-type dominance (65–75%) in the basement areas of Kano and Sokoto States, with H-type curves constituting only 10–15% of soundings. The mean longitudinal conductance values (0.013–0.890 mhos) reported in this study are comparable to those observed in the Zaria area (0.02–0.95 mhos) (Olayinka & Olorunfemi, 1992) and the Abuja area (0.01–0.85 mhos) (Abdullahi & Iheakanwa, 2013). The absence of stations with good protective capacity (S > 0.7 mhos) is consistent with the generally thin weathering profiles characteristic of the northern Nigerian basement (Lawal, 2021).

However, the extremely low S values at VES 09 (0.013 mhos) and VES 01 (0.034 mhos) are notably lower than the regional average, indicating exceptionally thin overburden in these locations. The significance of conducting geophysical investigations that are specific to a certain location is brought into focus by this discovery, which underlines the local-scale heterogeneity that is characteristic of crystalline basement terrains.

4.2.2 Implications for Groundwater Development

The conclusions of this study have a number of significant consequences for the development of groundwater in the Bauchi Metropolis, including the following:

i. Integrated Dar-Zarrouk-GIS provides a scientific basis for borehole siting, which is an important aspect of site selection. Rather than focusing on VES 09, 01, and 03, it is recommended that priority be given to VES 06 (the H-type curve) and VES 04 (the K-type curve).

ii. Protective Capacity: The majority of the groundwater developments in the research area have a protective capacity that ranges from poor to moderate, which implies that all groundwater developments need to utilise attentive wellhead protection procedures (Rajkumar & Xu, 2011; Falae et al., 2024). These measures include the following:
   - Concrete platforms that are elevated
   - Sanitary seals that are at least five meters deep have been installed.
   - Exclusion of areas suitable for the disposal of garbage and livestock from the vicinity of wells
   - Monitoring the water's quality on a schedule

ii Aquifer Vulnerability: Because there are no zones with enough protective capacity, the entire area under study is susceptible to contamination from the surface. If elevated trace element concentrations are found in wells that are situated in areas with a low protective capacity, then this vulnerability is proven. This will have severe repercussions for public health, particularly with regard to shallow hand-dug wells, which are prevalent in the region (Baguma et al., 2026).

iii Sustainability: Because of the restricted groundwater potential and the inadequate protective capacity, it is likely that the research area will have low concentrations of sustainable abstraction rates. The overexploitation of water resources may result in the induced recharge of contaminated surface water, which in turn may lead to a decline in water quality (Custodio, 2002).

4.2.3 Limitations of the Study

Several limitations of this study should be acknowledged:

1. Coverage of Space: The scope of the investigation was restricted to ten VES stations all located within Unity Estate. Despite the fact that this is sufficient to show the methodology, further data is required in order to extrapolate the findings to the full Bauchi Metropolis.

2. Dimensions of the Investigation The maximum AB/2 of sixty meters allows for an investigation depth of roughly twenty-five to thirty meters. In the event that deeper aquifers were present, they would not have been discovered.

3. Despite the fact that there was no pumping tests carried out, the hydraulic parameters of the aquifer were confirmed. Because of this, the classification of groundwater potential is determined by geoelectrical inference rather than by direct hydraulic measurements.

4. Temporal Variability: The geoelectrical data are a snapshot in time that represents the temporal variation. There was no evaluation of the seasonal fluctuations in the

depth of the water table or the quality of the groundwater.

4.2.4 Recommendations for Further Studies

Based on these limitations, the following recommendations are made:

1. Enhanced Geographical Coverage: It is recommended that additional VES stations be purchased in order to cover the whole Bauchi Metropolis. This will allow for the creation of a comprehensive vulnerability map.
2. In order to determine the sustainable yields, transmissivity, and storage coefficients, pumping tests should be carried out in the locations that have been suggested, specifically at VES 06 and VES 04, respectively. This will allow for the optimal determination of these parameters.
3. Repeated VES observations during both the wet and dry seasons would provide information on seasonal water table fluctuations and the influence these fluctuations have on the vulnerability of aquifers. This information would be important in the context of seasonal monitoring.
4. Incorporating additional geophysical methods, such as seismic refraction and electromagnetic, could provide additional constraints on the structure of the subsurface and complement the data on resistivity. This is referred to as geophysical complementarity.
5. Geological mapping, borehole logs, and data collected through remote sensing would be incorporated into the hydrogeological framework, which would result in an improvement in interpretation and a more comprehensive framework. The integration of data would be the means by which this would be accomplished.

4.2.5 Summary of Key Findings

1. Curve Types: A-type curves dominate (70%), with H-type (10%), K-type (10%), and HA-type (10%). The H-type curve appears at VES 06, which shows that the aquifer conditions are at their most favourable.
2. It was determined that there were three to four layers of geoelectricity, with resistivities ranging from 12 Ω·m (clay) to 3,115 Ω·m (fresh basement).
3. In terms of longitudinal conductance, the values of S range from 0.013 to 0.890 mhos. It is worth noting that fifty percent of the stations exhibit a low protective capacity ($S < 0.1$ mhos), while none of the stations demonstrate a strong protective capacity ($S > 0.7$ mhos).
4. Transverse Resistance: The values of T range from 4,776 to 21,010 $\Omega \cdot m^2$, with VES 06 exhibiting the lowest T value, which is associated with the maximum groundwater potential.
5. The values of the coefficient of anisotropy (λ) fluctuate between 1.23 and 1.58, which indicates that there is a moderate degree of vertical heterogeneity throughout the research area.
6. Groundwater Potential: VES 06 (H-type) is classified as high potential; VES 02, 04, 05, 10 as moderate; and VES 01, 03, 07, 08, 09 as low potential.
7. The protective capacity could be described as moderate (20%), weak (20%), bad (50%), or good (0%). Each and every part of the research area is susceptible to contamination of the groundwater.

8. Validation: The vulnerability classification is validated by the fact that hydrochemical investigation demonstrates that areas with low protective capability have elevated trace element concentrations.

5.0 Conclusions

A comprehensive evaluation of groundwater potential and aquifer protective capacity has been created as a result of the geoelectrical and Dar-Zarrouk parameter study performed on ten VES stations located at Unity Estate, Bauchi Metropolis. Based on the preponderance of A-type curves and the generally low longitudinal conductance values, it can be deduced that the area under investigation possesses a restricted groundwater potential and is extremely susceptible to contamination risks. The only station that exhibits favourable hydrogeological parameters that are consistent with a productive aquifer is VES 06, which is the only station.

The application of these findings to the management of groundwater in the Bauchi Metropolis has important consequences. Due to the high level of susceptibility that exists throughout the research area, it is imperative that all groundwater developments include strict preventive measures. The integrated Dar-Zarrouk-GIS technique that was examined in this study offers a framework that can be replicated for the purpose of evaluating groundwater resources in crystalline basement terrains that are comparable to those discussed here.

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